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Concepts for Improvement of Airport Surveillance Radars

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16. Abstract

This report reviews the performance of operational ASR's, discusses each type of clutter with which the target must compete, examines presently employed methods of overcoming clutter and several state-of-the-art techniques which have not found their way into the ASR's for one reason or another. It concludes by describing two radars, one at S-band and one at UHF, which are believed to come closest to fulfilling ASR requirements in advanced ARTS facilities.

The major improvements in performance will be derived from the use of linear optimum signal processing. Further gains will be achieved through the use of adaptive thresholds. STC will combat bird clutter. The radar will incorporate proper shaping of the antenna pattern so that aircraft off the peak of the antenna elevation beam will not be at a disadvantage compared to moving clutter at the peak. The recommended radar concepts also include radial velocity determination by Doppler measurement. This should prove of value in maintaining target tracks and in discrimination against ground vehicles.

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CONCEPTS FOR IMPROVEMENT OF AIRPORT SURVEILLANCE RADARS

I. INTRODUCTION

The objective of the ASR improvement program is to determine state-of-the-art radar and signal processing techniques which should be applied to the task of primary radar surveillance in the terminal area. The radar sensor concept chosen should be completely compatible with the objectives of the ARTS-III system and, in particular, it should provide the best possible primary radar tracking under all conditions within acceptable cost constraints.

This report is the output of a working group (see Appendix I) which examined the performance of the present ASR radars, improvement programs underway in both the FAA and military services and possible state-of-the-art improvements which could conceivably be applied to the primary radar surveillance problem. Inputs were received from engineering and management personnel within the FAA as well as controllers and other operational personnel. Contractors who have worked on ASR, ARTS-III and similar problems were contacted. Numerous reports, periodicals, books and symposia records were examined.

The general picture which emerged is that for manual operation the controllers usually rely on beacon replies, using the radar for backup in case of inoperative or nonexistent beacons. The general reliance on beacon over radar returns extends also into automatic tracking systems such as in ARTS-III, wherein all tracking at present is on beacon replies.

Primary radar tracking is done at Atlanta and Kennedy, but here the beacon reply is preferred because of the identity information it contains. Beacon tracks are initiated automatically whereas primary radar target tracks must be initiated by a controller. Atlanta reports that the percentage of time the track of a typical aircraft is coasting (being projected forward in the absence of a valid reply) is reduced from about 20% on beacon replies alone to about 4% when the track is augmented by radar replies. They report that a particularly critical time is just after take off when the aircraft banks in such a way that the beacon antenna is shielded. The track is usually lost without primary radar.

The ultimate goal for primary radar should be the capability of automatic initiation and tracking of all aircraft. To achieve this goal, better detection and false alarm performance is required, particularly in a clutter environment and for aircraft with near tangential velocities. Better mechanisms for associating successive target returns should also aid tracking.

We shall examine the problem in terms of the types of clutter which the radar must encounter and then go into the target tracking problem. Finally, we shall discuss radar concepts which we believe should be considered. We hope to show that these concepts can best be proved by the construction of two dissimilar type radars. These are the rotating-antenna radar at S-band and the step-scan antenna radar at a lower frequency (400 to 1300 MHz).

II. RADAR BACKSCATTER FROM AIRCRAFT

Before describing the clutter problem, a few words are in order concerning the radar target of interest. Very little data appears to be available on the radar cross section of small aircraft. The smallest we could find was that of a T-33 in an excellent report [1] which describes S- and X-band returns with both linear and circular polarization under a wide variety of conditions.

Figure 1 shows radar return from the T-33 averaged over 5° intervals for both linear and circular polarization. The sense of circular polarization used was that which would reject rain clutter. Note that near broadside, where the large specular return occurs, there is a large difference between linear and circular.

The region of low return near the front of the aircraft (± 60 degrees) was analyzed statistically. The cumulative distributions of amplitudes for the two polarizations are shown in Figure 2. They conform closely to the Swerling Case I model (within one dB). The Swerling Case I radar target model has a Rayleigh amplitude distribution and fluctuates from scan to scan but not from sweep to sweep within one dwell time.

For reference, the dimensions of a T-33 are as follows:

Length:	37 ft 8 in.
Wing Span:	38 ft 10 in.
Height:	11 ft 8 in.

Most private aircraft are smaller. A detailed knowledge of their radar cross sections would be most valuable in ASR system design.

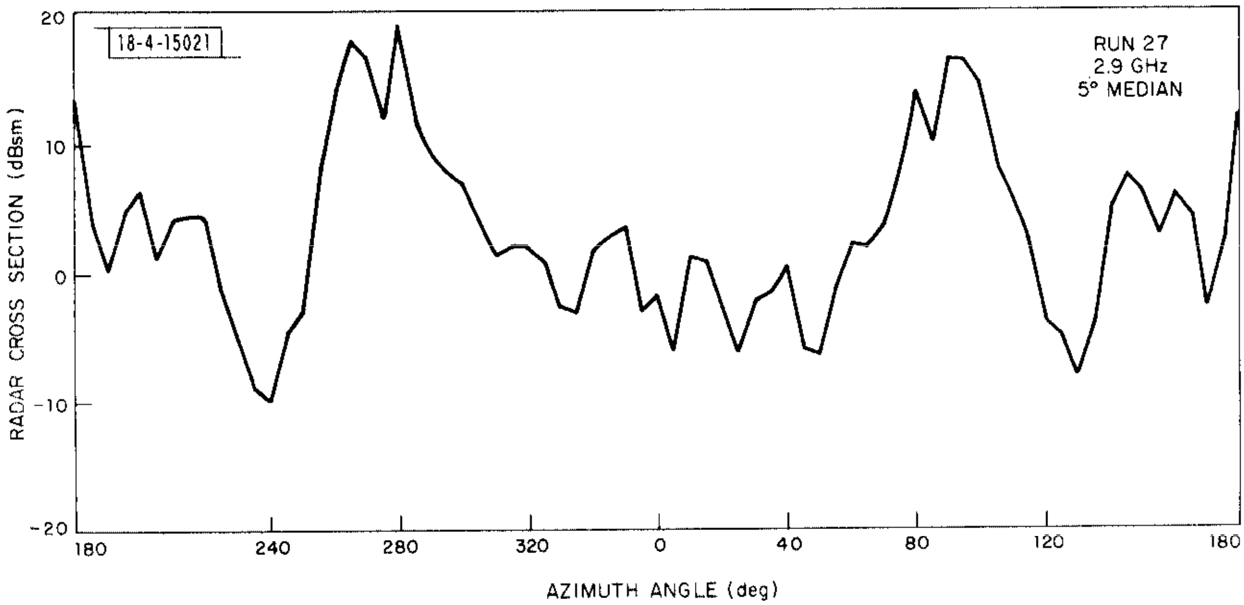

Figure 1a. S-Band Median Plot of Full Scale T-33 Aircraft (Vertical Polarization, + 5° Tilt) from Ref. 1.

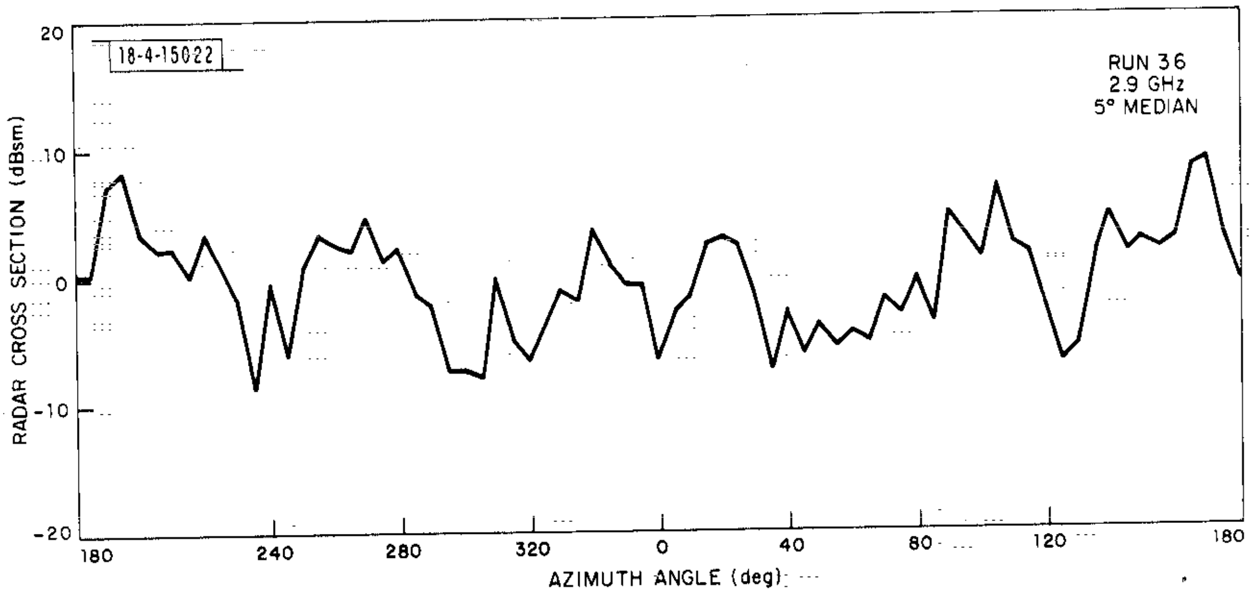

Figure 1b. S-Band Median Plot of Full Scale T-33 Aircraft (Circular Polarization, + 5° Tilt) from Ref. 1.

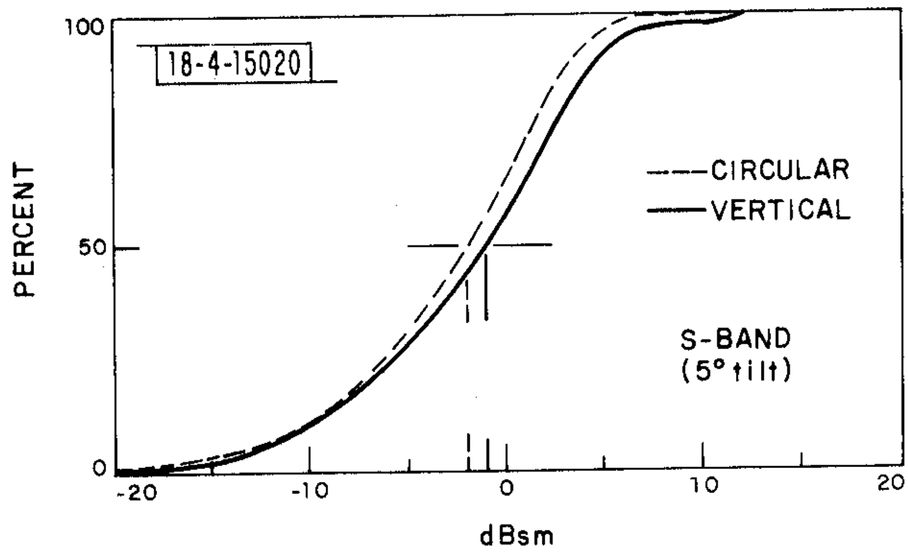

Figure 2. Cumulative Probability Distributions for Circular and Vertical Polarizations at S-Band ($\pm$ 60° Sector about Nose, T-33) from Ref. 1.

III. FIXED GROUND CLUTTER

By far the biggest undesired radar reflections come from fixed objects on the ground. Ground clutter extends out to about 20 nmi except in very hilly or mountainous areas where it may extend out to a maximum radar range (~60 mni). Its natural or intrinsic spectrum is very narrow compared to the spectral spread caused by antenna scanning motion.

Ground clutter varies appreciably from spot to spot in the area of coverage. Typical distributions of the mean values σ_o are shown in Figure 3. It tends to be highest from cities.

In the present ASR radars, ground clutter is reduced by three mechanisms, MTI, antenna tilt, and by mounting the antenna close to the ground to take advantage of the shielding effect of nearby objects. Figure 4 shows the MTI performance achievable using one and two delay lines with and without limiting. Previous ASR radars have all employed limiting in the IF followed by a phase detector. The purpose of the limiting is to normalize the video output so that clutter is reduced to the normal noise level. This allows the video gain to be adjusted so the clutter will not show up on the scope. Unfortunately, this limiting action spreads the clutter spectrum so that considerably poorer subclutter visibility (SCV) is achieved than if the normalization had been done by some other mechanism not involving nonlinearities.

If we consider the ASR-7 parameters at 15 nmi, and a σ_o from Figure 3 that is exceeded only 5% of the time, we find that for a one-square-meter target the input signal-to-clutter ratio is -31 dB. Since an output signal-to-clutter ratio of about 10 dB is needed for adequate target visibility, an improvement factor of 41 dB is required. We see from Figure 4 that this

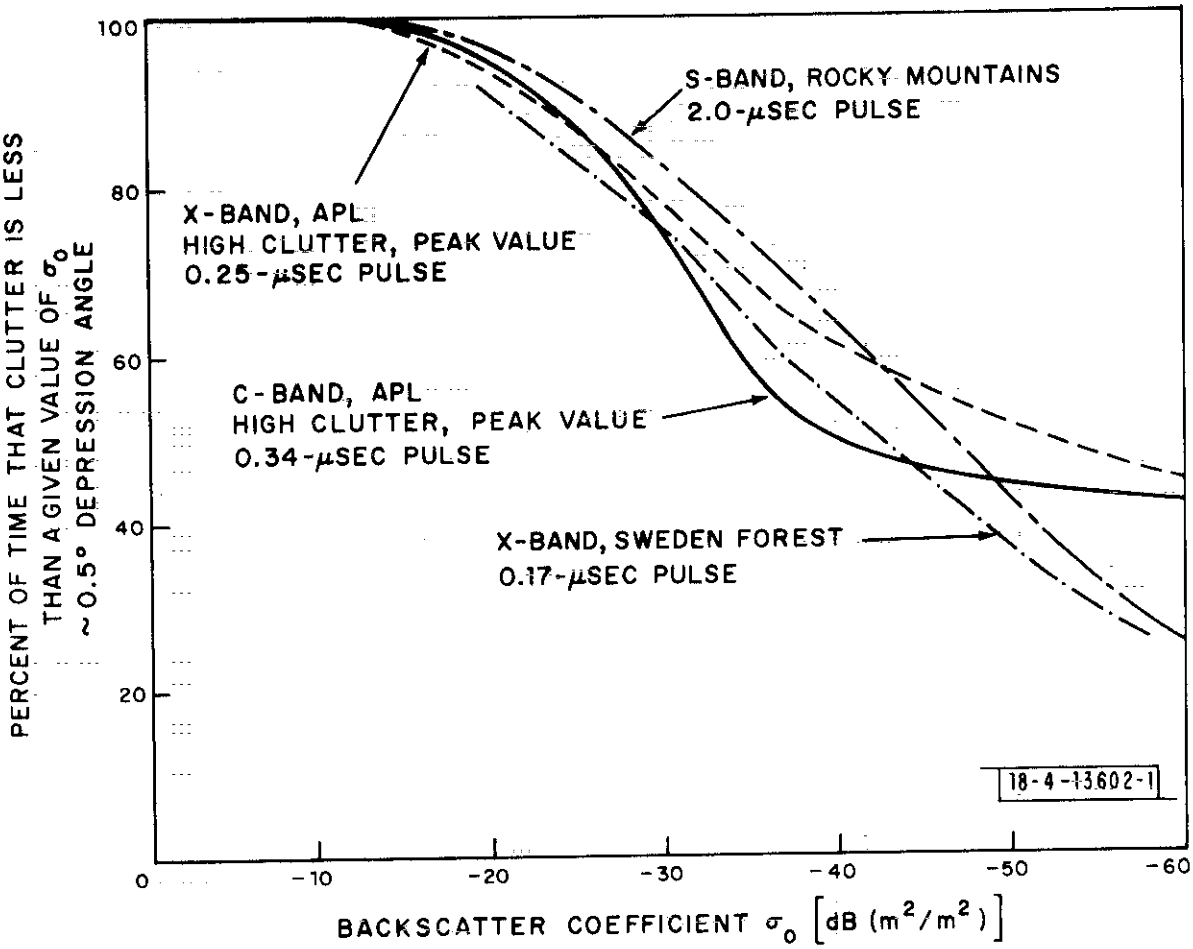

Figure 3. Land Clutter Backscatter Distribution from Surface Radars from Ref. 2.

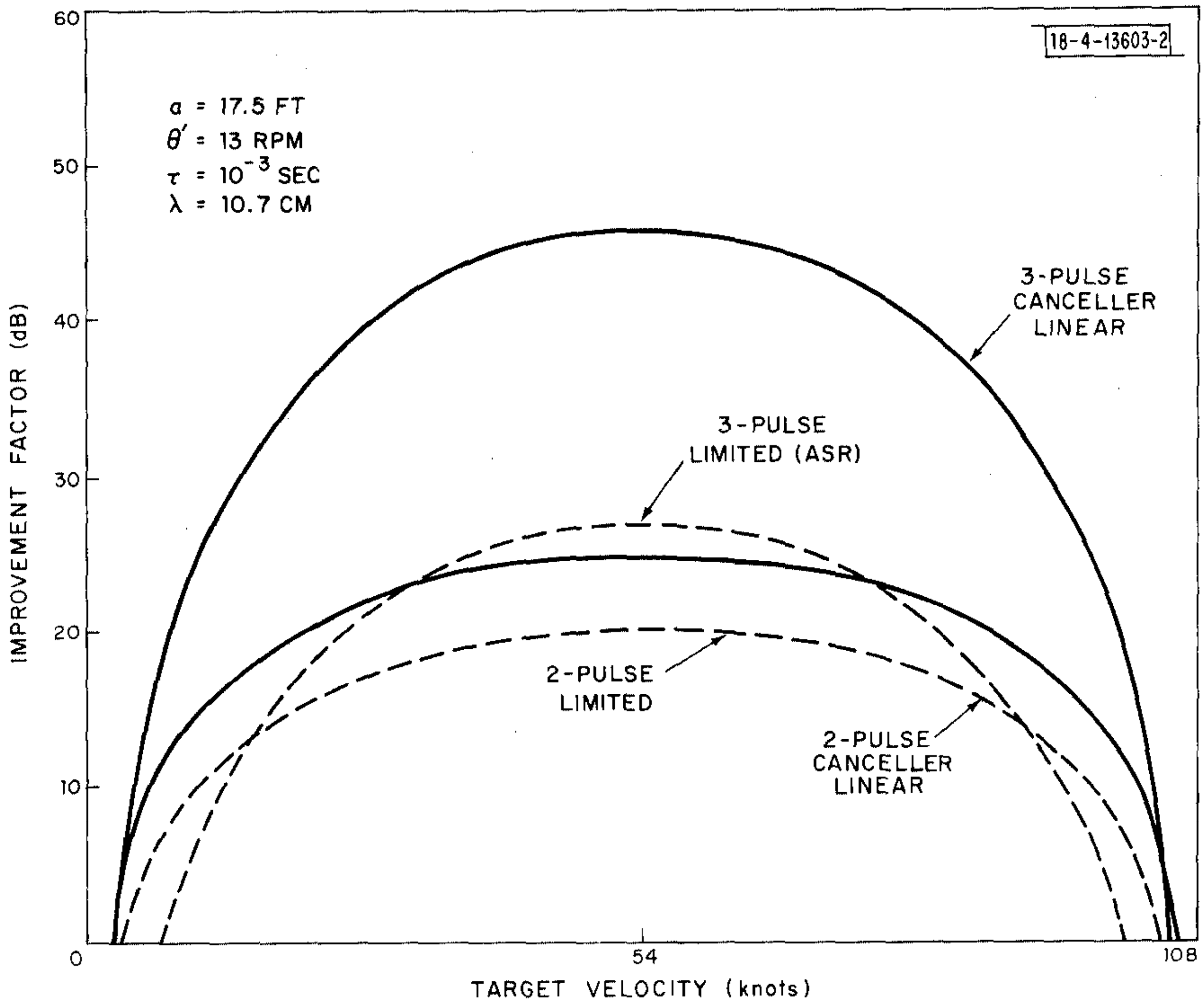

Figure 4. Performance of S-Band Cancellers. The Improvement Factor is the Ratio of Signal-to-Clutter Out of the Canceller to Signal-to-Clutter In. The Latter ASR Radars use 3 Pulse Cancellers Following a Limiter.

is not achievable with the present configuration. It is, thus, common practice to achieve greater signal-to-clutter advantage by tilting the antenna upward (see Figure 5) by two to five degrees depending on the local clutter situation. If tilted, as shown in Figure 5, there is a 17 dB advantage in input signal to clutter for an aircraft flying in the peak of the antenna pattern. This advantage is degraded as the aircraft gets out of the peak of the antenna pattern so that, typically, detection gets spotty due to competition with ground clutter for small aircraft below about 1.5^{o} or above about 9^{o}. These angles change depending on the antenna tilt and ground clutter intensity. It is estimated that a 20 dB increase in improvement factor would be required for really adequate detection of small aircraft at all altitudes.

Another undesirable feature of the improvement curves of Figure 4 is the very wide notch around zero and the first blind speed. The notch around zero means that targets will be lost for a considerable distance on the scope when the aircraft flies tangential to the radar. It will be observed that the three-pulse canceller with limiting is worse in this respect than the two-pulse canceller with limiting. Below, we shall describe how more advanced signal processing techniques can both provide a large degree of improvement in SCV, and much better performance near zero velocity.

A further limitation in performance of present ASR's is the presence at many sites of buildings or hills which limit the minimum elevation visible to the radar. Elevation of the antenna to overcome this limitation causes an undesirable increase in ground clutter level.

At some sites, in mountainous regions, second time around clutter is a problem.

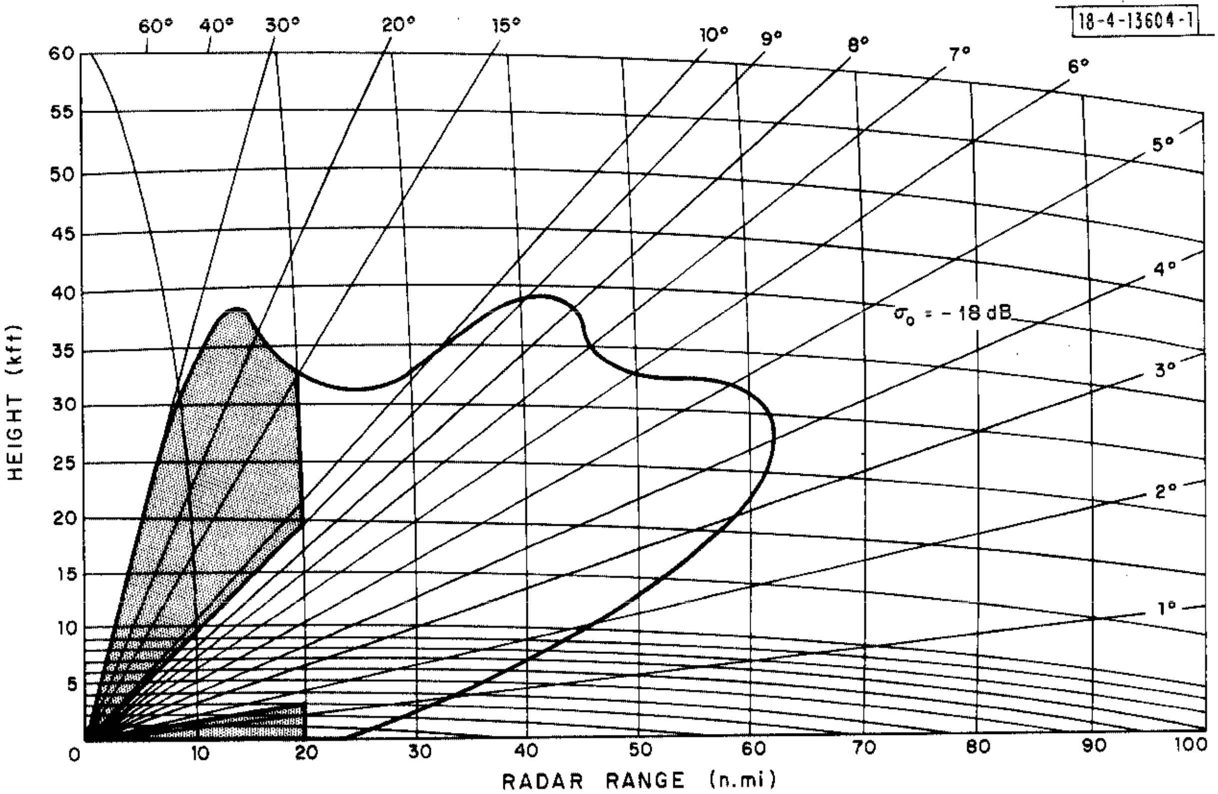

Figure 5. Solid Curve is Coverage of ASR-7 Radar Against a 2 m^2 Target in Receiver Noise. (Ref. 3) Cross Hatched Region Shows Region of Poor Performance Against Ground Clutter.

A. Optimum Signal Processing

In order to assess quantitatively what could be considered a "good" MTI processor for improving the performance of ASR radars against fixed ground clutter, calculations have been made of the performance of the so called "optimum processor." Given the initial conditions, the optimum processor has the highest target-to-interference (interference is defined as clutter plus front-end noise) ratio improvement of any processor. By knowing the performance of such a processor, one can judge whether a conventional easily implemented or any other processor (i.e., suboptimum) can approach the theoretical limit. The processor considered here can be defined as a device that takes M complex signal returns V_i, multiplies these returns by a complex filter weight $\bar{W}_i$, adds them and then takes the square of the amplitude

$$R = \left| \sum_{i=1}^{M} \bar{W}_i \, V_i \right|^2$$

V_i is composed of target, noise and clutter. The theory of optimization will not be shown here but follows that of Delong and Hofstetter [4]. The clutter spectrum which in this case is essentially all caused by the antenna scanning motion is modeled by an antenna having a Gaussian beam shape as in Emerson [5].

Two general cases have been studied: the mechanically rotating antenna as in the ASR radars and, the step-scan antenna. In both of these cases the transmitter pulses are uniformly spaced. Figure 6 shows the

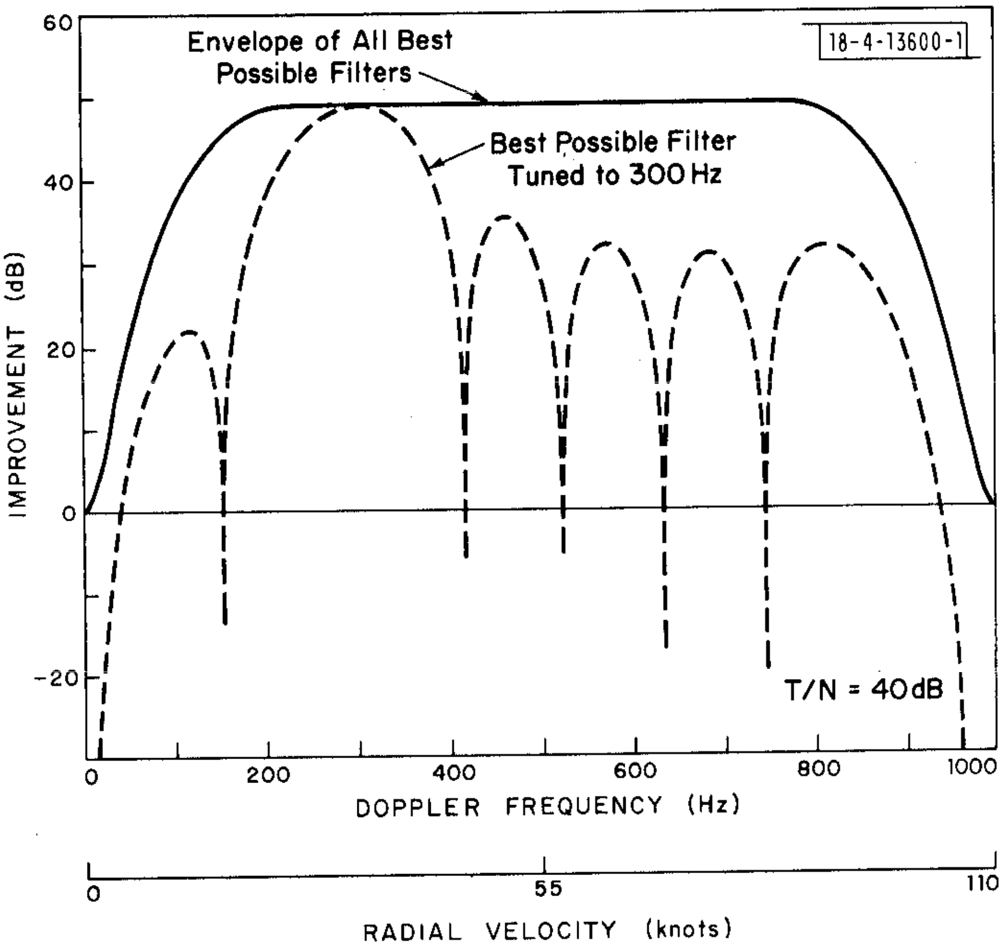

Figure 6. Improvement of Target-to-Interference Ratio, Scanning Antenna.

target-to-interference improvement in decibels that is possible (optimum) for the mechanical antenna*. The parameters are (similar in most respects to the ASR-7):

Antenna Width	5.24 meters
Antenna Rotational Speed	1.36 radians/sec.
Wavelength	0.107 meter
PRF	1000 pulses/sec.
No. of Pulses Processed/Look	10
Clutter-to-Noise Ratio	40 dB

The maximum clutter-to-noise ratio which can be handled will be set by the dynamic range of available analog-to-digital (A/D) converters. If the peak clutter signal corresponds to the range in the A/D converter, clutter-to-noise ratios of 40 to 50 dB can be handled in available A/D converters with adequate sampling rates.

The optimum processor requires a priori knowledge of the clutter-to-noise ratio, however, this ratio can be determined in principle by the application of a proper algorithm in the receiver.

The upper curve in Figure 6 is the improvement obtained when the optimum filter is tuned to the Doppler frequency of the target as the target Doppler is varied. The lower curve is the improvement when the optimum filter is tuned to a fixed Doppler (300 Hz) as the target Doppler is varied. The lower curve also represents the frequency response of the optimum filter tuned to 300 Hz.

---

*The results in this section assume the use of a sufficiently stable, coherent transmitter. Poorer, as yet undetermined, results will be obtained using a magnetron transmitter.

The following general characteristics of these curves should be noted:

1. The upper curve levels out at about M x C/N = 10^5 where M is the number of pulses processed and C/N is the clutter-to-noise ratio, unless M is small. This points up the need for wide dynamic range A/D converters as explained above.
2. At the so called "blind speeds" (0 and 1000 Hz), there is no deterioration either, thus a target that is above clutter can be seen.
3. For filters that are not tuned on or close to blind speeds, there are very deep nulls at the blind speeds.
4. The width of the notch about the blind speeds increases with antenna rotational speed when all other parameters are held constant.
5. The filter cannot in general be approximated by a Discrete Fourier Transform (DFT) except in certain special cases.

The step-scan case is shown in Figure 7. Because the antenna is not scanned and ground clutter can be considered to be time stationary (constant voltage), the clutter spectrum is just an impulse at zero frequency. The intrinsic ground clutter spectrum (motion of trees) is ignored because it is too narrow to have any effect upon the results. It should be pointed out that the only input parameters needed for the step-scan case are the PRF, the number of pulses per look (M) and the clutter-to-noise ratio. Thus, these curves are directly applicable to other radar frequencies as well as S-band. The parameters used in Figure 6 are the same as in the scanning case.

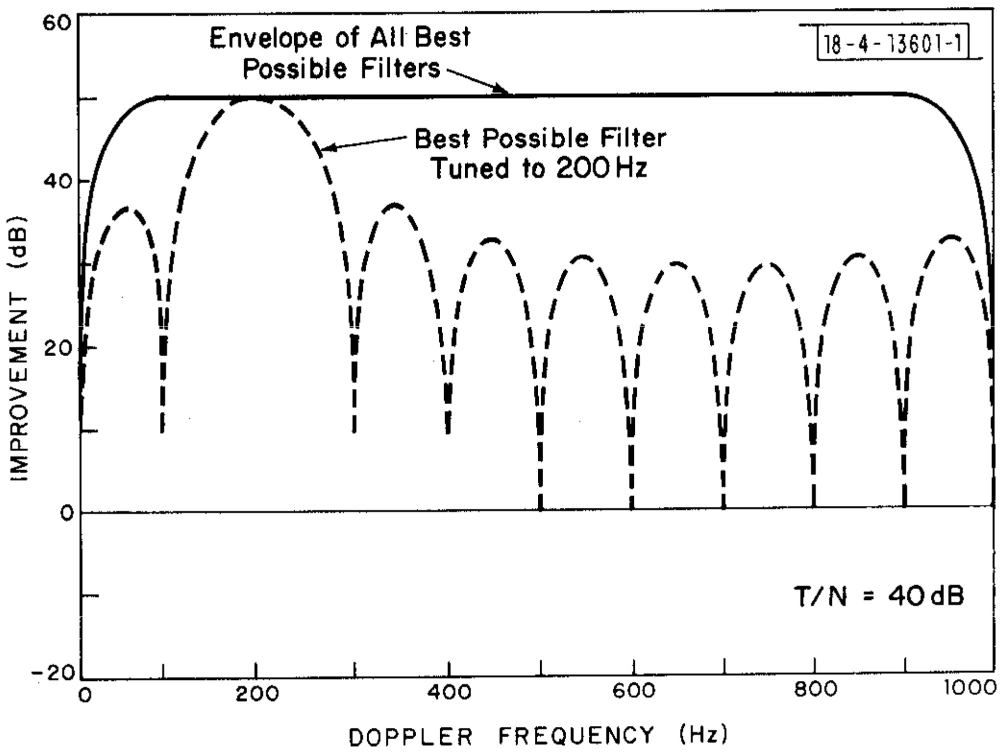

Figure 7. Improvement of Target-to-Interference Ratio, Step-Scan Antenna.

The following properties of the step-scan curves (Figure 7) should be noted:

1. The notches at the blind speeds are now very narrow. There would be much less change of losing a target in clutter with near tangential velocity.
2. In most instances a DFT can replace the optimum filter and thus improve computation efficiency.
3. Although it cannot be seen on this figure, the improvement at the "blind speeds" is 0 dB as in the scanning case of Figure 6.

By comparing these results with those of Figure 4, we see the amount of clutter rejection achieved in the present ATC systems as well as other conventional MTI systems is far less than the best that can be done, whether scanning or not.

B. Near-Optimum Signal Processing

In the scanning antenna case, the implementation of the optimum processor for every range-azimuth cell calls for M complex multiplications for each target velocity examined. Usually, if M pulses are being processed, a filter bank with M filters will give adequate coverage for all target velocities. Thus, M^2 complex multiplication must be performed for every range cell. For a typical ASR, 800 range cells per sweep must be collected on 10 sweeps and processed every 10 msec. If then pulse optimum filters were used, 8,000,000 complex multiplications per second would be required or 32 million simple multiplications.

A simpler processor can be built. The optimum processor can be broken into two parts, a clutter filter followed by a target filter. The filter used to reduce clutter multiplies the signal vector by the antenna weighting and by the inverse of the interference covariance matrix. The target filter used to enhance the target is a Discrete Fourier Transform. The near-optimum processor could consist of a digital filter which approximates as closely as possible the frequency response of the clutter filter followed by a noncoherent integrator in place of the target filter. This combination will give improvement factors within a few dB of the optimum shown in Figure 6 and require fewer multiplications per second than indicated above. It will, of course, not provide any Doppler information on the target. A possible solution to the ground clutter problem then is to do near-optimum processing to determine the presence of a target in the range-Doppler cell. After detection of a target a Discrete Fourier Transform which uses coherent integration can be performed, if desired, to obtain target-Doppler information.

At the present time, the exact form of the algorithm for the near-optimum clutter filter in the ASR scanning antenna case is not known. Its frequency response is known and from this the filter configuration can be derived. For the step-scan case, Figure 7, the clutter filter is nothing more than a dc removal filter and so is very easy to implement.

C. Linear Processing

In order to achieve the performance indicated in Figure 6 and 7, it will be necessary to avoid any nonlinearities in the receiver and use two-channel (quadrature video) processing. This will necessitate different thresholding techniques as discussed in Section IV, E.

D. Step-Scanned Antenna

Besides the ease in implementing a near-optimum processor when an electronically step-scanned antenna is used, the resulting performance curve yields very narrow notches at zero velocity and the blind speeds. These are so narrow (Figure 7) that in all likelihood it would not be necessary to stagger PRFs to overcome blind speeds.

Electronically step-scanned cylindrical antennas have been developed at UHF and one is being developed at L-band for ATCRBS use, but no suitable cylindrical antenna has yet been developed at S-band. Using a suitable feed, it is possible to step-scan a mechanically rotating antenna [14]. The results obtainable using optimum processing in this case have yet to be studied.

E. Shaped Elevation Antenna Pattern

As was observed earlier, detection is spotty for targets at high elevation angles (about 9° in Figure 5) at ranges where ground clutter exists. An elevation pattern other than cosecant squared [6] would mitigate this problem. Particularly, the gain should be approximately constant with elevation to solve this problem as well as the bird problem discussed below. Some compromise may have to be made with the constant gain approach since this implies a lower gain antenna and consequently less range on targets competing with receiver noise.

F. Dual-Beam Antenna

The performance of the ASR in detecting low flying aircraft at long range should be improved considerably using optimum or near-optimum linear processing as this will allow depression of the present antenna beam. If this proves inadequate, especially if the antenna is elevated to help overcome local line-of-sight problems, it should prove beneficial to provide a second receive-only antenna beam with its peak pointed quite close to the horizon. This beam, due to its narrower elevation beamwidth, would have more gain than the higher beam so that it could detect weak targets at long ranges where ground clutter is not a problem.

G. Multiple-Beam Antenna

The next logical step in antenna improvement beyond (E) and (F) above is to provide a set of elevation beams on receive, transmit or both. One might, for instance, transmit a cosecant squared beam and simultaneously receive on a number of narrow elevation beams. The upper beams will contain very little ground clutter so will need no ground clutter filters. They will, however, at times contain precipitation clutter requiring a precipitation filter in addition to circular polarization for each range cell in each receive beam. These filters, described below under precipitation, will require a number of pulse returns and will be more complicated than the ground clutter filters.

One solution to the problem is to lower the operating frequency sufficiently so that rain returns are not a problem. Then no precipitation filtering would be required.

An alternative approach, at S-band, to having precipitation filters in each beam might be to form one or two fan beams in elevation with filtering in each. Then, only when a target is detected, each elevation beam would be filtered for the range gate involved to determine the height of the aircraft. This would still require storage of the returns from each elevation beam over several pulses.

IV. PRECIPITATION CLUTTER

The backscatter from precipitation has been studied extensively. Figure 8 shows the mean volume reflectivity from rain at 15 mm/hr. This is considered a heavy rain found only 0.04% of the time at New Orleans[2]. This heavy rainfall is usually found only in relatively small size cells in the center of storms.

Also marked on Figure 8 is the point where the volume reflectivity is such as to cause a one-square-meter return at 30 miles in an ASR radar (rain return from a typical cell with precipitation extending from the surface to 10,000 ft.). Rain at 15 mm/hr is about 13 dB above this value. Remembering that these are average reflectivities and that ~15 dB signal-to-noise ratio is required for automatic detection, we need about 30 dB rain rejection for good performance.

The rain clutter spectrum is spread around some mean value determined by the wind velocity. The spectral spread observed by the radar is fixed by wind shear conditions[2]. The standard deviation of the rain velocity spectrum typically reaches values of 4 m/sec at 30 nmi.

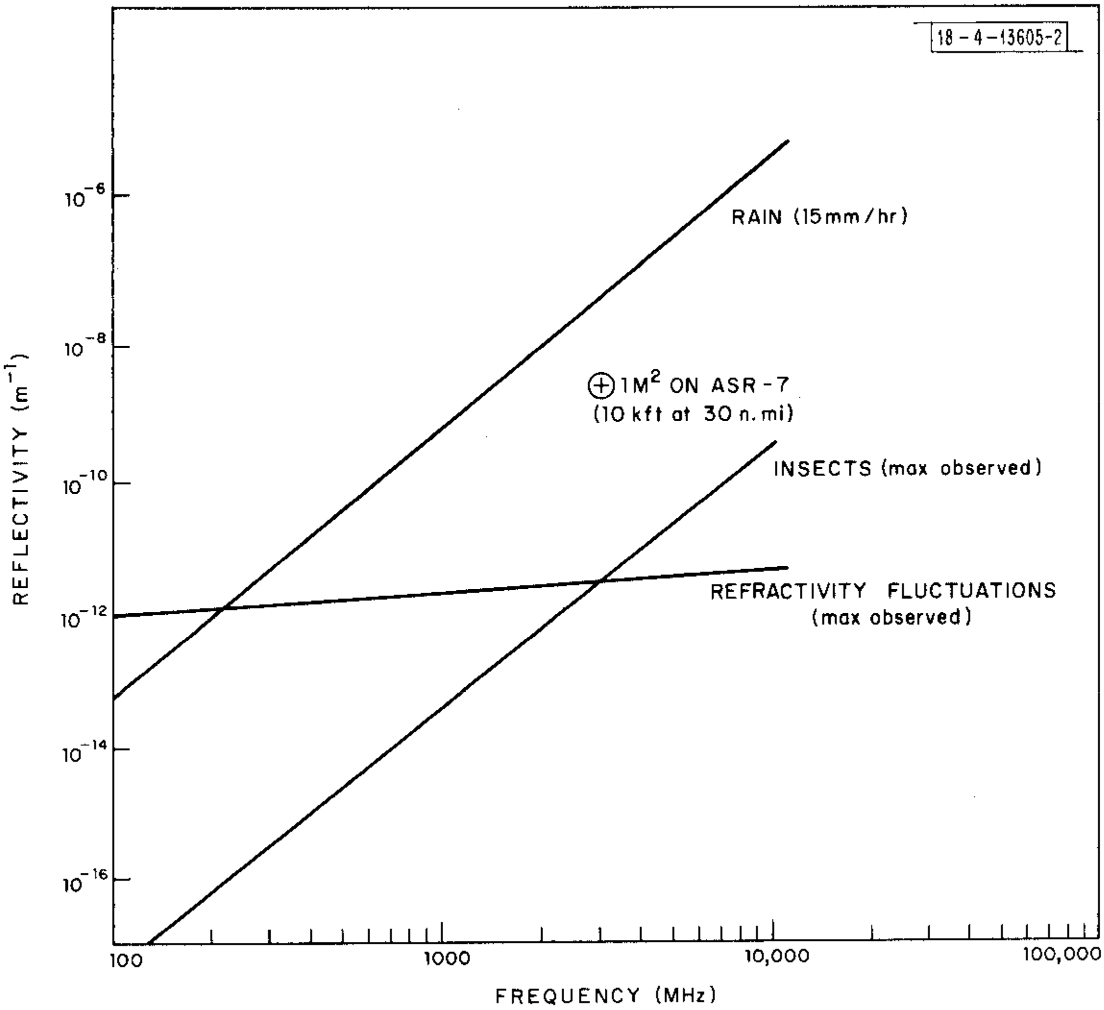

Figure 8. Reflectivity of Various Moving Clutter Sources. (Ref. 2, 7)

Circular polarization is normally used to reduce rain clutter by about 15 dB while reducing the signal level to some extent. The use of MTI helps reduce rain clutter except when the antenna is looking toward or away from the wind direction. In these directions the rain clutter spectrum is such that a considerable amount may pass through the MTI filters.

Log-FTC-antilog circuits[3, 8] are used to normalize the rain clutter level just as limiting is used to normalize ground clutter at the output of the MTI circuit. Its purpose is to suppress the rain clutter on the scope. At the same time, of course, it suppresses the signal. The signal amplitude must be appreciably above the clutter amplitude for adequate detection.

It has been suggested that the use of pencil beams in elevation would alleviate the problem. Reasonable pencil beams still have about two degrees beamwidth. This may reduce the precipitation clutter by three dB below that shown in Figure 8, an insignificant improvement.

The use of much finer range resolution has been suggested. To be of much value, the range resolution should be improved by a factor of 15 to 30 with a consequent increase in bandwidth to 15 to 30 MHz. Considering the difficulty of obtaining wideband frequency allocations and the need for ground clutter filtering in every range cell, this does not appear to be an attractive solution.

A. Circular Polarization

As mentioned earlier, transmitting one sense of circular polarization and receiving on the same sense will result in a reduction of return from nearly spherical rain drops. Careful measurements [9] with an antenna with a very high degree of decoupling between the polarizations shows that there is a natural limit of about 15 dB in rain cancellation by this method due to the non-spheroidal shape of the drops. Besides this, circular polarization causes a reduction in target return, especially specular returns off the side of an aircraft[1] (see Figure 1). For this reason it would be beneficial to have available for processing both senses of polarization on receive. When the radar detects the presence of precipitation in an area, the receiver channel with the lowest return should be used. However, Figure 1 indicates that better results may be obtained in detecting near tangential targets by using linear polarization even in rain.

B. Elliptical Polarization

Recent work has shown that the process of reflection from and propagation through precipitation is quite complex and that the use of circular polarization to remove rain clutter is not optimum. Rain in general is an anisotropic propagation medium for electromagnetic waves (the droplets are roughly ellipsoids) and as a result converts circular polarization into elliptical. This causes the circular polarization cancellation to worsen as the rain path length increases. Thus, better cancellation occurs near in, where the path length is short. Experiments[9] have been performed where the transmitted signal has been modified to be elliptical in order to compensate for the rain path length. That is, the operator adjusts the ellipticity to improve the cancellation. Improvements greater than eight dB above that attained using circular polarization are common. However, adjusting the transmitter ellipticity would in general compensate only for one range. In principle, it should be possible to adjust the receiver to be orthogonal to rain clutter for all ranges independently. An adaptive type of algorithm would be needed which would measure the ellipticity of the signal and then adjust the receiver ellipticity. This could all be accomplished digitally. The real and imaginary components of the left-hand and right-hand polarization (or horizontal and vertical) are fed into a digital filter. The processor would then construct the orthogonal digital processor. The effectiveness of such a method depends on how well the ellipse remains correlated both in time and space. It is not clear how difficult it would be to implement such a system.

C. Doppler Filtering

At S-band it may well be necessary to use some other mechanism besides circular polarization to reduce the effect of precipitation clutter. Merely setting the threshold higher which is what is done by the log-FTC-antilog scheme is not enough since this desensitizes the radar for all target velocities.

An effective solution is to filter out the precipitation clutter and then set the thresholding discussed in Section IV, E. It is equivalent to the log-FTC scheme except that an arithmetic mean is employed instead of a geometric mean to establish the threshold.

Two types of filters can be considered. A notch filter could be built in which the center frequency and width of the notch are adjusted to match the precipitation spectrum. Alternately, a filter bank could be build with the output of each filter thresholded. The latter approach fits nicely with the optimum signal processing concept used for ground clutter since this also involves the implementation of a filter bank.

D. UHF Operation Frequency

Another very attractive approach to the elimination of precipitation clutter is to lower the operating frequency. The backscatter return varies with the fourth power of the frequency. Using circular polarization, approximately another 15 dB of clutter rejection is required. This would be provided by operation at 1100 MHz or below. Circular polarization could also be eliminated by operation at 500 MHz or below.

There is a definite frequency allocation problem involved but it should be pointed out that the band 420 to 450 MHz is presently set aside for government radio location use. UHF radars in the 600 MHz band using mechanically scanned antennas are already being built and sold for ATC applications around the world. Some 50 to 60 of these radars are in operation.

E. Thresholding

Precipitation as well as other transient forms of clutter causes the clutter level and thus the appropriate detection threshold to change with time and space. Somehow a threshold value must be derived from the radar system for each resolution cell examined for targets. There are a limited number of possibilities. For a particular cell, depending on the type of resolution built into the radar, the threshold might be derived by averaging clutter in nearby range cells, nearby azimuth cells, nearby elevation cells, nearby Doppler cells, or by averaging clutter from the cell being examined for a target at times when it probably does not contain a target (other scans). We shall call this last method time-average thresholding and the first four methods intrascan thresholding since all the data required to derive the threshold is produced by the radar during one scan. Limiting MTI, Log/FTC and IAGC/FTC are all forms of intrascan thresholding.

The whole subject of thresholding against clutter appears to have received very little attention[10]. No one seems to have tackled the very interesting theoretical question of what is the best way to derive a threshold level when clutter, particularly nonstationary clutter, is the interference. It is all handled on an ad hoc basis.

The type of thresholding to be used depends also on the type of filtering. An S-band ASR with a filter bank in each range azimuth cell might require an inordinately large memory to implement a time-average threshold for each resolution cell. A compromise may be made wherein the zero-Doppler cells use a time-average threshold and the others use an intrascan threshold based on the level of clutter in nearby range cells in each Doppler filter. At sufficiently low frequencies, on the other hand, where rain is not a problem all thresholds might be derived in a time-average manner.

Much more information is required to refine thresholding methods. In particular, we need to know the amplitude statistics of each form of clutter (ground, weather, birds) and the correlation of the important statistics (mean, variance, etc.) as a function of range, azimuth angle, elevation angle, Doppler and time. It appears that this information can be obtained only be measurement. Using these, the theoretically best form of threshold together with its performance can be ascertained.

V. BIRD CLUTTER

Returns from single birds[11] at S-band range in size between 10^{-4} and 10^{-2} square meters. The return is principally from the body with very little from the wings. For large birds, the body is resonant near L-band (1300 MHz) and is in the Rayleigh region at UHF. Typically, there may be anywhere from one to several hundred birds in a resolution cell. Although the mean return from a typical flock of birds may be low ($\sim 10^{-2}$ m^2) the tail of the distribution has been observed to return up to 10 m^2. Although birds have been seen as high as 12,000 ft altitude, they usually fly less than 7,000 ft. The ususal appearance on the scope is as so called "dot angels." 'Ring angels" are also caused by birds as a large group of birds leave their nesting place at sunrise.

Of particular interest, are the bird migrations in spring and fall. These have been described as "night effect," "falling leaves," "seasonal AP angel clutter," and have been reported by many terminals in the eastern part of the United States. The appearance on the scope when the radar is using MTI is that of two well defined lobes. In Figure 9, there is a strong migration in an easternly direction so MTI notches appear north and south. The lobes appear to be made up of a multitude of spots which move like falling leaves.

These migrations occur at night when there is a favorable wind. Migration will be very heavy on favorable nights so that most of the migration occurs on relatively few nights (five to 15) each spring and fall. The number of birds associated with these migrations may be very large. One author estimated that a few million birds crossed a 100-mile front during one of the busy nights of the autumn migration in the Cape Cod region[11].

Birds fly between 15 and 45 knots true air speed. Taking into account winds, radial velocities over the range ± 80 knots or so may be observed.

The only radar improvement used against bird clutter is a carefully tailored sensitivity time control (STC)[12]. The STC is adjusted so that the minimum detectable target is a specific value, say, one m^2. This calls for an R^{-4} attenuation law.

A. Antenna Elevation Pattern

STC for bird elimination will not work properly when a cosecant squared antenna pattern is used. An aircraft at the same range but at a higher altitude will suffer due to the lower antenna gain in the direction of the aircraft. The ideal antenna pattern would be a constant gain with elevation angle up to the cut-off angle of 30 degrees. Unfortunately, this pattern shape would require more power from the transmitter (~18dB) or an equivalent increase in sensitivity. Some of this can be made up by better processing

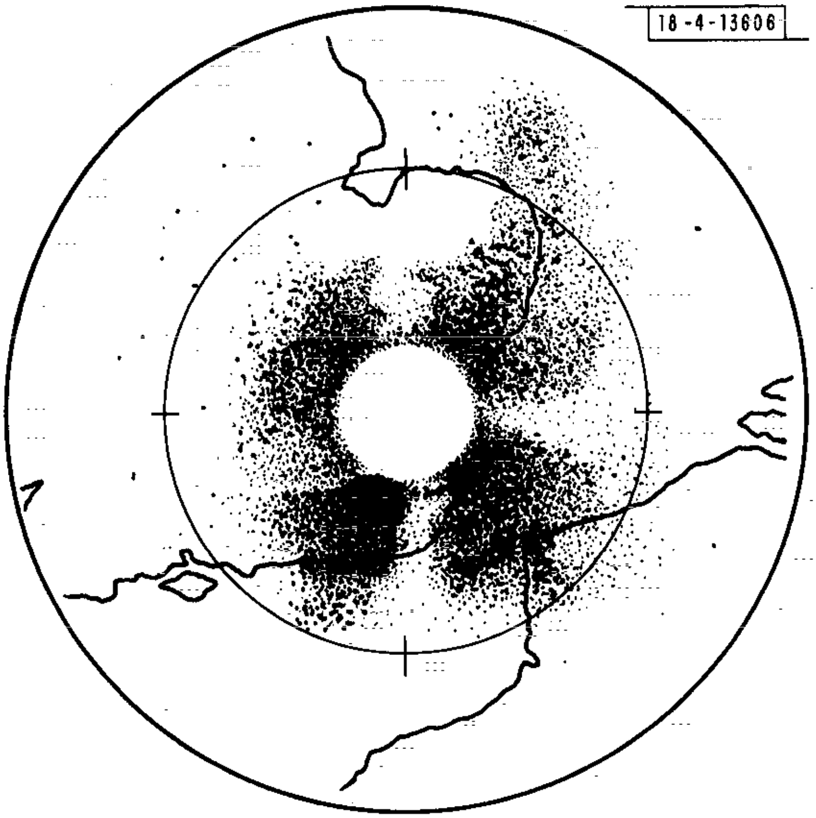

Figure 9. Migrating Birds As Seen Using MTI Radar from Ref. 11.

and some by reducing the range requirements to closer to 40 nmi. Perhaps a better way would be to use an antenna similar to that of the ARSR-2 wherein the gain in the upper elevation angle region is lower than the peak[6] by about 8 dB but is nearly constant. This would give the birds only 16 dB antenna advantage but make the increased sensitivity requirements very small (~3 dB).

B. UHF Radar

Shift of the carrier frequency to UHF would greatly reduce the bird clutter return. The largest birds are resonant near L-band so that their clutter return is reduced by a factor of about 15 dB at UHF (400 MHz). Returns from smaller birds would be reduced by a larger factor.

VI. SURFACE VEHICLES

The cross section of ground vehicles is in the same range as aircraft; namely, from one to 100 m^2. Radial velocities range over ± 60 knots.

Some reduction in ground vehicle returns is achieved by tilting the antenna upward. The only other solution found so far, as is practiced in Atlanta, is to blank out targets in scope sectors known to contain visible roads carrying cars with radial velocities outside the notch at zero velocity. This has proven effective and causes only small holes in the coverage.

A. True Velocity Demonstration

If the radar were configured so that target Doppler was measured and Doppler ambiguities were removed, then the true radial velocity of targets would be known. This is added information which the tracker could use to ascertain that the target is an automobile on a known road. In Section VIII, we discuss methods of removing Doppler ambiguities to determine true radial velocity.

B. Target Height Determination

Height information could also be used as a discriminant to reject surface vehicles. Height information is discussed in Section VIII.

VII. OTHER CLUTTER SOURCES

A. Superrefraction

Sometimes, the vertical lapse rate of the refractive index becomes much greater than normal due to atmospheric conditions. This condition causes the electromagnetic waves to be bent down so as to intersect the ground at various distances. This effect can greatly extend the range at which ground clutter is a problem.

As yet, we know little about how superrefraction effects the ASR's, particularly the Dopplers likely to be introduced onto the returns from the distant ground clutter.

B. Insects and Refractivity Turbulence

Swarms of insects have been observed by meteorologists using powerful radars [7]. The swarms may cover large areas and in general, drift with the wind.

Well organized layers of turbulent refractivity in the atmosphere associated with changes in the refractive index have been observed.

The maximum volume reflectivity associated with these types of returns is plotted in Figure 8. It will be observed that both are much lower than heavy rain returns so should cause little difficulty when trying to detect one-square-meter aircraft.

VIII. TRACKING REQUIREMENTS

We shall discuss three topics in this section. The first relates to detection and false alarm requirements in order to acquire targets in track rapidly and to avoid losing them. The general conclusion is that a probability of detection of 0.7 or better (blip-scan ratio) and a false alarm rate of 10^{-5} or less per range-azimuth resolution cell are adequate.

The second subject deals with the possible use of Doppler or radial velocity information to aid tracking, and how unambiguous radial velocity is determined. The third subject deals with methods of obtaining height information and its value to tracking.

A. Detection and False Alarm Requirements

The ultimate goal of the radar is to provide data of high enough quality to satisfy the input requirements of a tracking computer. If this goal is fulfilled, the radar output would also be suitable for PPI display and manual interpretation of tracks.

From the point of view of detection and false alarm requirements, the generally accepted criteria for adequate tracking are stated in terms of the rapidity with which aircraft are put into track, the absence of false tracks, the computer load required and the ability of the tracker to hold onto a target once acquired (track life).

A reasonable set of rules for an automated ASR might be:

1. New aircraft targets coming within the field of view of the radar should be put in track with high probability within some fixed period of time. This period is established by the distance an aircraft can safely travel before he may, with very small probability, collide with another aircraft. We shall take this period as five scans (20 to 25 sec.).

2. The rate of false track production should be very low in a fully automated system. If we take three miles as the desired separation distance and if there are about 200 aircraft within the radar's field of view, it is highly probable that any one false track will cause concern resulting in an avoidance maneuver. We take the view that false tracks should be very infrequent and set the rate of false track initiation at one per hour.

3. The computer load involved in handling false alarms should be only a fraction of that associated with true targets; thus, the false alarm rate should not exceed about 20 per scan.

4. Once an aircraft is in track it should not be lost easily. Studies of optimum tracking procedures[15] indicate that using output from the present ASR's, four successive misses can be tolerated. If this is the criteria for breaking a track and we want the probability of a broken track to be low, (say, 0.005), then the single scan probability of detection should be greater than 0.734.

To investigate the impact of the first three rules on radar requirements, an analysis was performed to relate the radar parameters to the ability of the tracker to establish tracks. The results are shown in Figure 10.

Several criteria for establishing a track were examined. Each criterion involved the same length of time (five scans). Some required detection on two, three, or four scans (2/5, 3/5, 4/5) and one required detection on two successive scans within the five (2/2 in 5). For each case, the relation between the false track generation and the false alarm rate was established, assuming the first false alarm anywhere and successive false alarms to be within a search bin containing 300 range-azimuth cells. The actual number of resolution cells usually used varies above and below this value depending on detection history and target ranges. A constant value was used to make the computation simpler.

For each case, a false alarm rate was chosen (see Table I) so that the rate of initiation of false tracks is one per hour. Using these false alarm

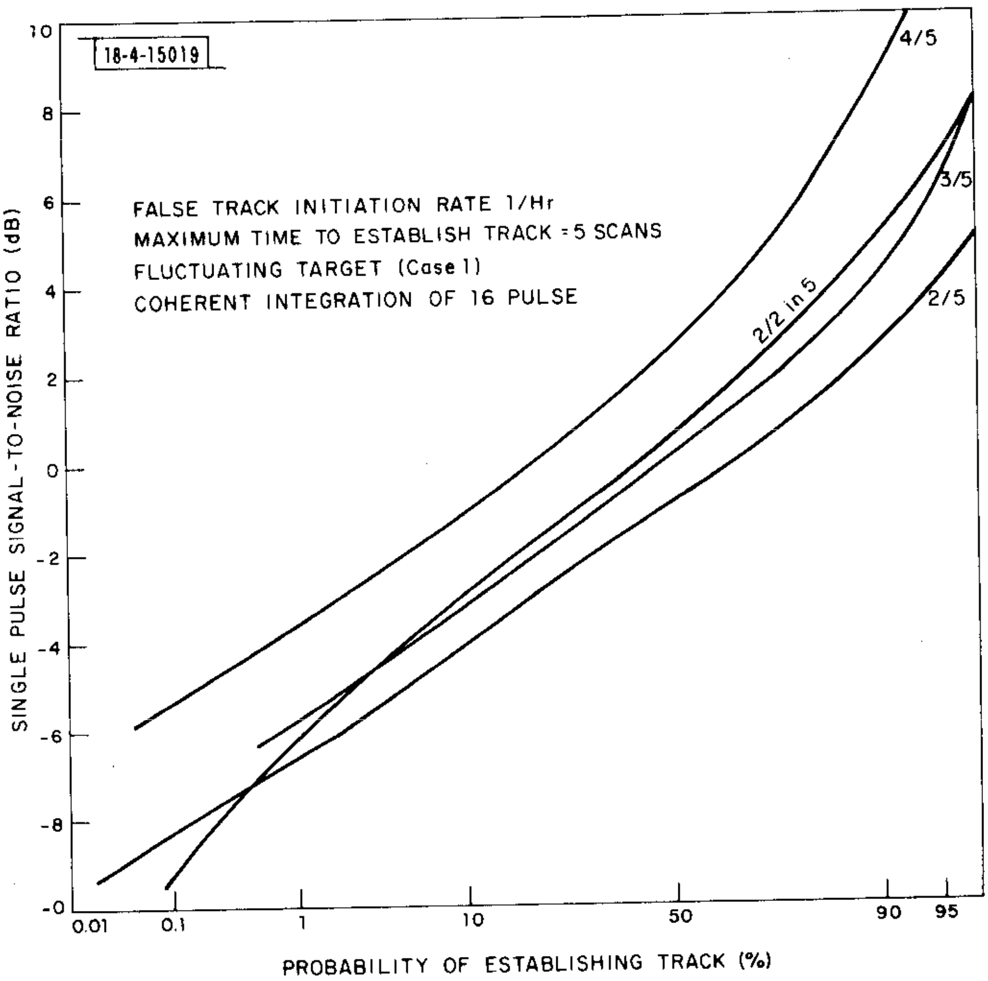

Figure 10. Signal-to-Noise Ratio Required to Establish a Track.

rates and data from a detection probability graph for fluctuating targets (Swerling Case I) the probability of establishing a track was calculated for each case (see Figure 10).

Table I. Rate of False Alarms.

Rate of Initiation of False Tracks	One per hour
Maximum Time to Establish Track	Five Scans
Fluctuating Target (Swerling Case I)	
Coherent Intergration of 16 Pulses Per Dwell	
P_{fa} = Probability of False Alarm Per Range-Azimuth Resolution Cell	
Cells in Search Bin	300
Cells in Area of Coverage	300, 000

Case	P_{fa}	False Alarms Per Scan	S/N for 0.734 P_d	Probability Of Track Initiation
2/5	2.2×10^{-6}	0.66	3.5 dB	0.94
3/5	2.2×10^{-5}	6.6	3	0.83
4/5	8.6×10^{-5}	25.8	2.5	0.49
2/2 in 5	5.4×10^{-4}	1.62	3.2	0.80

The results show that the more lenient rules require lower signal-to-noise for any probability of establishing track. All of the rules examined result in reasonably low false alarms per scan.

To complete the picture, the fourth colum of Table I shows the required signal-to-noise (S/N) ratio to avoid losing tracks (fourth rule). Finally, column five uses this S/N to find the probability of establishing a track for each case studied.

The results show very little difference in performance between the lower three cases in Figure 10. The above analysis tacitly assumes the noise to be Gaussian. This can be considered true when the interference is white noise or precipitation clutter. Ground clutter processors with inadequate dynamic range will suffer from clutter residue feed-through and may not be able to maintain the low false alarm rates indicated above.

B. Radial Velocity Information

At first thought it would appear that the addition of measured radial velocity information to the target reports would add greatly to the ability of the tracker in the correlation process by reducing the search bin size, and in the case of crossing tracks, by velocity discrimination.

First, in regard to the crossing track problem, an S-band ASR while processing eight pulses coherently could provide a velocity resolution of 12 knots and even better accuracy. The trouble is that if an aircraft is allowed half-g accelerations during four-second periods, its velocity uncertainty would be $\pm$ 38 knots which is a good fraction of the 120 knot velocity ambiguity region. It would, thus, be necessary to resolve velocity ambiguities on every scan. For the case of crossing tracks with the two aircraft in the same or adjacent resolution cells, the situation would be quite confused and little value could be made of the Doppler information. If UHF were used, Doppler ambiguities would not exist so the information would be useful in track crossing situations. Even here, however, two aircraft with radial velocities within $\pm$ 38 knots could not be distinguished.

Next, considering the target report correlation process, the search bin would have a third dimension; namely, radial velocity. The search bin dimension in radial velocity is determined by acceleration uncertainties. The reduction in the range dimension of the search bin allowed by some knowledge of radial velocity is largely counter-balanced by the extension in this third dimension so the false alarm rate stays nearly constant. However, a somewhat larger signal-to-noise ratio is required because of the desire for a positive detection on both PRF's used to resolve ambiguities.

At UHF, the picture is different since the velocity uncertainty due to unknown accelerations is comparable to the velocity resolution so that fewer velocity cells are examined for a target. Also, all of the radar's energy can be expended in one look for the target instead of splitting it up into two PRF's.

The following sections discuss various methods used to resolve ambiguities at S-band.

1. Multiple PRF's During One Dwell Time

If the dwell time is sufficient, two or more series of pulses can be transmitted at different PRF's sequentially. A Doppler filter bank is used for each PRF and the ambiguity resolved by observing the change in position of the target amongst the filters. The two-way beam width of the ASR antenna is about one degree. If the rotation rate were changed to 10 rpm, the dwell time would be 16 msec. Two groups of eight pulses each could be transmitted on PRF's spaced about 10% apart centered around 1000 Hz. This would resolve ambiguities over the region ± 550 knots and at the same time practically eliminate the blind speed near 110 knots, assuming the use of optimum Doppler filtering.

2. Interleaved PRF's on Different Carriers

Multiple PRF's could be realized by interleaving two or more PRF's on carriers spaced a few megacycles apart. The two return signals would be filtered from one another and processed separately and the ambiguity resolved as above. Chosen about as described under (1), the same results would be achieved except that twice the power would be transmitted so the antenna speed of 15 rpm could be maintained. Since the receiver could not operate during a transmitter pulse and the associated recovery time, range rings would be blanked on both PRF's. These would be narrow and if the PRF's are integrally related, the same range rings would be blanked all the time so the target drop-out would be minimal.

3. Two Widely Spaced Carriers

Two pulses could be transmitted either simultaneously or in quick succession but at carrier frequencies spaced about 10% apart. On receive, the returns are filtered separately for each frequency to determine Doppler. Since velocity is related to Doppler frequency by the equation $f = 2v/\lambda$, we see that a 10% change in λ will move the Doppler sufficiently to resolve ambiguities and overcome blind velocities. Some difficulty will be experienced with frequency allocations and extra transmitting equipment with this scheme.

4. Staggered PRF[13]

A staggered PRF may be employed. If a two period stagger is used and processed, using a Discrete Fourier Transform, it is found that a single target will fall into two filters with amplitudes depending on its Doppler ambiguity region. Thus, in principle, one could unambiguously determine the Doppler. Unfortunately, returns from a single aircraft are likely to fall into several

Doppler filters even for a constant PRF due to engine modulation, so this method of velocity measurement is probably unreliable.

5. <u>UHF Carrier Frequency</u>

If the carrier frequency were changed to about 430 MHz, velocity would be unambiguous between ± 350 knots and there would be no need for more than one PRF.

C. Height Information

To understand the value of height information to ATC, it is wise to review the record of mid-air collisions. The records of all ten of the mid-air collisions during the period 1968 to 1971 involving a commercial carrier aircraft were reviewed [16]. During this period, no collisions between carriers occurred. All were between a carrier and a general aviation aircraft except one between a carrier and a military aircraft.

The remarkable aspect of these collisions is their similarity. All occurred in terminal areas. In each case, the larger aircraft was changing altitude (nine down and one up). All involved a condition of poor visibility. Most were passing through clouds. One had its windshield covered with bugs. In one, the smaller aircraft was invisible against city lights. Typically, the small aircraft would be flying several hundred feet below the clouds. The larger aircraft would break out of the clouds practically on top of the smaller aircraft.

You say, "Why didn't ATC divert one of the two aircraft?" In five out of ten cases the pilot of the larger aircraft was given an advisory concerning the presence of the small aircraft. The present rules in mixed airspace call for the pilot of the IFR aircraft, given such an advisory, to ask for a rerouting if he so desires. In the actual accident cases, the pilot did not see the smaller aircraft and did not ask for a rerouting. In these five cases, a rule change forcing an avoidance maneuver could prevent such accidents. Such a change of rules for low or medium density terminals would probably be acceptable. At high density terminals, however, an excessive number of such collision avoidance maneuvers might result and it is clear that a knowledge of both aircrafts' altitudes would be valuable in providing a smooth traffic flow.

In the remaining five out of ten cases, the smaller aircraft was not seen on the radar or at least advisories were not issued. Thus, without visual contact the accident was unavoidable.

The questions of height accuracy required and how it should be obtained are still open. Transponders are required on all aircraft operating in our larger terminal areas. Yet, there are nonbeacon-equipped intruders. Although a good fraction of the general aviation fleet carry transponders, very few have digital encoding altimeters. Also, direct measurements on general aviation aircraft show that more than 10% of their transponders are either inoperative or out of tolerance [17]. A good case could thus be made for primary radar height determination, especially in the busier terminal areas.

For the present, we believe that radar should first be improved so that it will reliably see the smaller aircraft. The consequences of a decision to build a radar incorporating height finding are discussed in Section III, G.

IX. IMPROVED ASR RADARS

A. S-Band Radar

In this section we draw from the large set of solutions to particular problems described above and present a set which should solve all the problems and allow automatic acquisition and tracking of primary radar targets. Table II lists the systems features to be included and the problem each helps solve.

Table II. S-Band Radar.

System Feature	Problems Helped
More antenna gain at higher elevations	Bird clutter, high elevation aircraft
Dual antenna beams	Longer-range, low elevation aircraft
Circular polarization	Weather clutter
STC with R^{-4} law	Bird clutter
Linear optimum processing, quadrature video detection, ground clutter map	Ground clutter, weather clutter, tangential aircraft
Two PRF's per dwell time	Blind speeds, target track association

It was first thought that a near-optimum ground clutter notch and a movable weather notch of adjustable width should be provided but it turns out to be approximately as easy just to provide an optimum eight-pulse processor. Two sets of 11 pulses (three extra for clutter notch filter and second-time-around ground clutter rejection) each would be transmitted sequentially at PRF's about 15% apart. Besides getting rid of blind speeds and providing a method of removing Doppler ambiguities, this procedure has two other advantages. The 11 complex samples can be examined for possible nonlinearities by observing if any reached the limit of A/D converters. The system would be built so that it was perfectly linear up to this level. If nonlinearities are detected among the samples, no detections would be allowed in that range gate. Secondly, by processing this way, azimuth can be broken up into groups (as well as range) in deciding whether to apply circular polarization or not. In fact, signals from the thresholding device could be used to decide if rain is present in each sector or not. This information would be fed to a small memory used to control the sense of circular polarization used in each sector on the next scan. A further advantage to constant PRF over stagger PRF when a klystron is used is the elimination of a second-time-around clutter effect.

The thresholding to be used would be configured after measuring the clutter statistics as described in Section IV, E. This threshold would be compared to a fixed threshold representing a fixed size target (perhaps, 1 m^2). The higher of the two thresholds would be used. The fixed threshold, together with STC and a more uniform elevation antenna pattern, should eliminate birds. The variable threshold will eliminate weather clutter in the filters containing it. Since all the weather should occur in one or two filters, a large percent of all possible Dopplers will be detected as if no rain existed. This process is aided further by the use of two PRFs since it will cause aircraft to show up in different filters.

In this system there is no distinction between normal and MTI video. Each target signal is coherently integrated over eight pulses so video integrators (or enhancers) are of no value and there is no question of choice between normal and MTI. Even zero velocity targets are processed as well as is possible and are seen if their signal levels are sufficiently above the clutter.

The need for azimuth monopulse has not been established at this time. The accuracy achievable by making amplitude comparison between the returns on groups of eight pulses is about 0.2 degree. Studies may indicate that this is accurate enough. If much better accuracy is indicated, then monopulse should be added to the radar. This involves design of a new feed, supplying a rotary joint and receiver channel for monopulse and adding an amount of memory equal to that used to store sum pattern returns. No added processing is involved since the difference signals would only be processed upon target detection in the sum channel, adding a very small precent to the total processing load. The sum channel processor would be time shared to do this job.

Target reports would contain amplitude, range, azimuth, and apparent Doppler. In a tracking computer, part of the ARTS-III, these reports would be processed to remove Doppler ambiguities, track targets and disregard targets which are probably surface traffic because of their low radial velocity and their position of known roads. It appears that no feedback is required from the tracking computer to the signal processor.

There are two major portions to these ASR modifications. The first involves a new antenna reflector and feed assembly incorporating the first three items in Table II and the second a new receiver-processor. These modifications could be built as replacement kits for any of the existing ASR radars. The processing would work better on the ASR-8 with its more stable klystron amplifier than on the older radars. A small interface could be built to convert target reports to display signals on older systems where tracking is manual. All this equipment should be located in the radar shelter. The output in digital form would be sent to the ARTS-III or display area.

These modifications would make the radar into a hands-off device as far as the controller is concerned. Detection would be optimized for him automatically under all clutter conditions.

B. UHF Radar

We have pointed out at several points throughout the report the advantages of a lower frequency. Table III lists features which would be contained in such a radar.

Some things listed in Table II do not appear here because the shift to UHF minimizes two problems direcly. First, bird clutter is reduced by at least 15 dB and weather clutter by 33 dB. There is no need for circular or elliptical polarization. Second, the Doppler ambiguity problem is eliminated so there is no need for multiple PRFs.

Table III. UHF Radar.

System Feature	Problems Helped
Electronically step-scanned antenna	Blind speeds, tangential aircraft
More antenna gain at higher elevation	Bird clutter, high elevation aircraft
STC with R^{-4} law	Bird clutter
Linear optimum processing, ground clutter map	Ground clutter, tangential aircraft
UHF frequency	Birds, weather clutter, Doppler ambiguities

The electronic antenna step-scanning reduces the width of the clutter spectrum so that the blind speed near zero is less of a problem. A less obvious advantage is that the optimum processor turns out to be easily implemented with a Fast Fourier Transform. The larger aperture greatly reduces the average power requirements of the radar. There is probably less target scintillation at UHF. Better system stability is more easily achieved. As explained in Section III, G, UHF would allow the use of elevation beams whereas the complexity of precipitation filters in each beam at S-band might rule it out.

The only factors which weight against UHF are more difficulty in obtaining frequency allocation and perhaps a somewhat higher cost, although this is questionable. UHF has a lot to recommend it and should be considered seriously.

X. CONCLUSIONS

In this report, we have reviewed the performance of operational ASR's, discussed each type of clutter with which the target must compete, examined presently employed methods of overcoming clutter and several state-of-the-art techniques which have not found their way into the ASR's for one reason or another. We concluded by describing two radars, one at S-band and one at UHF, which we believe come closest to fulfilling ASR requirements as employed in the ARTS-III system.

The major improvements in performance will be derived from the use of better signal processing. Further gains will be achieved through the use of adaptive thresholds; STC will combat bird clutter. The radar will incorporate proper shaping of the antenna pattern so that aircraft off the peak of the antenna elevation beam will not be at a disadvantage compared to moving clutter at the peak.

The forms and features chosen for the S-band and UHF radars in Section IX should not be considered as the final answer. These should be considered as the most promising radar concepts known today within reasonable cost constraints. As more is learned about the radars, details will change.

An important part of ASR development in the near future will be the study of the different forms of clutter as described in Section IV. E to determine the best thresholding methods. A strong theroetical as well as experimental program in the filtering and thresholding areas is indicated.

The recommended radar concepts include velocity determination by Doppler measurement. This should prove of value in maintaining target tracks. Height determination appears to complicate the radar excessively since, besides the requirements for multiple elevation beams, it will be necessary, at S-band, to do precipitation filtering in each beam. It is felt that the first order of business is the implementation of a fan beam radar better suited for automatic tracking.

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APPENDIX I

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